High Precision Spectrometers for Very Forward Protons in CMS

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Abstract. We plan to add proton tracking and timing detectors at z = 240-250 m on both sides of CMS to study central exclusive production, with one or both protons measured, and single diffraction. They provide measurements of $p+p \rightarrow p+X+p$, where $X = Z, H, W^+W^-$ and multiparticle states (with or without jets), as well as single high mass diffraction in low pile-up runs.

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Plans to add very forward proton detectors at $z = \pm 420$ m from ATLAS and CMS, called FP420, to measure *exclusive*[1] Higgs boson production, $p+p \rightarrow p+H+p$ were developed starting in 2003 in a series of "Manchester Meetings" [1], following ideas developed in 1998-2000 [2, 3, 4]. The cross section is in reach at the LHC if high luminosity, L $\sim 10^{34}$cm^{-2}s^{-1}, with $\sim$25 collisions per bunch crossing every 25 ns, can be used. This requires [2] precision timing ($\Delta t(pp)$) on the protons to get a vertex z_{pp} to match the z_{vertex} of the Higgs candidates, which, together with kinematic constraints, can reduce pile-up background to a manageable level. (If good timing is added to the central detectors, additional pile-up rejection is possible.) The forward proton detectors are small, $15(x) \times 12(y)$ mm^2, and with silicon pixel detector stacks spaced by 10 m we can measure the position and angle, (x, θ_x), to about (10 μm, 1 μrad). In order to have acceptance for a 125 GeV Higgs boson, $H(125)$, with both protons measured, there has to be at least one station at z = 420 m after 120 m of superconducting dipoles. There is a missing dipole there, and a cryogenic bypass can be installed to expose a room-temperature beam pipe; also the machine optics is ideal. At this location the deflected protons, with fractional momentum loss $\xi = 1 - p_z/p_{beam}$, are between the two beam pipes and space is limited, so traditional "Roman pots", as used since the early ISR days, are not possible. We have developed a different type of vacuum chamber, a "moving pipe", initially used by ZEUS at HERA. A 40 cm section of vacuum pipe has a thin flat wall (pocket) on one side, and when the beams are stable the pipe (between bellows) is moved sideways to bring the detectors within 2-3 mm of the circulating beam. Unlike Roman pots, there are no differential forces involved, and the pockets can have much more space for the detectors, while being compact in the x-direction. Our plan is to have two pockets per beam; the first with silicon pixel tracking detectors, and the second also with timing detectors [5], with $\sim$ 10 ps resolution, at the back.

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[1] Exclusive means no other particles are produced.

A report on the FP420 R&D project, which was joint venture between both ATLAS and CMS physicists, was published [6] in 2009. Following that period, the ATLAS and CMS groups proceeded semi-independently, calling the proposed subdetectors AFP (ATLAS Forward Protons) and HPS (High Precision Spectrometers) respectively. I report on the HPS. We proposed a two-stage approach: Stage 1 is at $z = \pm$ 240-250 m, where the vacuum pipe is clear of obstruction and installation is straightforward. However the acceptance for $M(X)$ = 125 GeV with both protons detected is small and only at high momentum-transfer squared -$t \gtrsim$ 4 GeV^2. In Stage 2 we add stations at 420-430 m, where a cryogenic bypass must be made. In addition to the high acceptance for H(125) with both protons measured, the (120 m $\times$ 8T) dipoles between 240 m and 420 m give much better momentum resolution. (The magnets upstream of 240 m are quadrupoles, 28 Tm of warm dipoles to separate the beams, and a 35.9 Tm superconducting dipole to bring the beams parallel.) In Stage 1 the full set of detectors can be made operational and a physics program started with $M(X) \gtrsim$ 200 GeV, and one or two years later the cryogenic bypasses could be installed to complete Stage 2.

At 240 m the scattered protons are not between the beam pipes but towards the outer (larger radius) wall, This means that in principle Roman pots can be used there, if the longitudinal (z) space limitation is not an issue [2]. In Stage 2 there is not space.

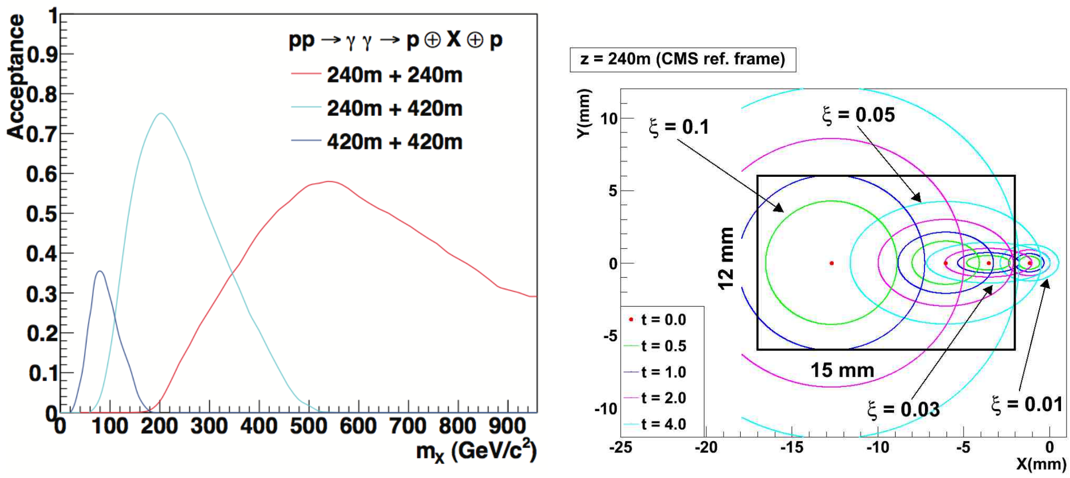

FIGURE 1. Left: Acceptance at small t for both protons detected at different stations. Right: Contours at fixed t, ξ in the x, y plane at 240 m. For any t, ξ the acceptance is approximately the fraction of the ellipse contained in the detector area (-6mm $< y <$ +6mm, -17mm $< x <$ -2mm).

The *acceptance* in Stage 1 includes Z and $H(125)$ with one proton measured, but not with both. The acceptance, see Fig.1, includes 0° scattering for $0.015 < \xi < 0.12$, which allows photon exchange to be detected. The t measurement can be important to distinguish γ and $\mathbb{P}$ exchange. These figures are for a detector active edge at 2 mm from the beam center (at 3 mm the acceptance is reduced for $\xi \lesssim 0.02$). For $p + H(125) + p$

[2] After this Workshop different scenarios are under evaluation, including the possibility of Stage 1 using Roman pots at 240 m or 204-216 m.

the best acceptance is with 240+420 m stations, but the mass resolution is best with 420+420 m. The 240 m (but not the 420 m) detectors are near enough to be included in the level 1 trigger.

I now discuss some physics that can be done in Stage 1 with detector stations at 240 m with both protons measured, $p+X+p$, and acceptance $M(X) \gtrsim 200$ GeV. Later I consider what may be done with a single proton measured, with acceptance down to lower $M(X)$ but with fewer constraints. The production of a state X between two large rapidity gaps in $pp(p\bar{p})$ can occur through three processes [7]: $\gamma+\gamma$ (QED), $\gamma+\mathrm{I\!P}$ (photoproduction), and $\mathrm{I\!P}+\mathrm{I\!P}$ (double pomeron exchange). The following processes were observed for the first time (in $p\bar{p}$) by CDF: $\gamma\gamma \to e^+e^-, \mu^+\mu^-$, $\gamma\mathrm{I\!P} \to J/\psi, \psi(2S)$, and $\mathrm{I\!P}\mathrm{I\!P} \to \chi_{c0}, \gamma\gamma$, and dijets. At the LHC the higher energy opens up central exclusive production as a new window on *electroweak* processes, thus: $\gamma+\gamma \to W^+W^-, \gamma+\mathrm{I\!P} \to Z$, and $\mathrm{I\!P}+\mathrm{I\!P} \to H$. Stage 1 only has acceptance for the first of these reactions, unless there is a heavier Higgs. We have now discovered a state at 125 GeV, and it is important to measure its properties every way we can. Looking like a Standard Model Higgs, it may be an MSSM SUSY h^0, partnered by a heavier H^0, with $M > 200$ GeV. A state coupling mostly to fermions has much less background in $\tau^+\tau^-$ than in $t\bar{t}$ and $b\bar{b}$. In *inclusive* $\tau^+\tau^-$ the mass resolution is poor because of the missing neutrinos, but in exclusive production with $p_T(\tau^+\tau^-)$ small and one or both protons measured, an overall fit can be done and the $M(\tau^+\tau^-)$ resolution improved to only a few GeV.

The $\gamma\gamma \to W^+W^-$ reaction is guaranteed, with a SM cross section $\sigma(WW, M > 300)$ GeV $\sim$ 50 fb. This is a factor $\sim$20 larger than the $\gamma\gamma \to \mu^+\mu^-$ cross section, because the t-channel exchange is $J = 1$ rather than $J = \frac{1}{2}$ [7]. The W are transverse and do not access the Higgs sector, but this channel is sensitive [8] to anomalous quartic gauge couplings. In 10% of the events both W decay leptonically (e, μ, τ) so they can be triggered on, the QCD background is absent, and the kinematics fully constrained. Requiring no other tracks within 1 mm of the dilepton vertex cleans the signal with little loss of efficiency. The cross section $\sigma(\gamma\gamma \to x\bar{x})$ depends only on the charge, spin and mass of the particle x. Although charged sleptons can be pair-produced, the cross section is much too small because the t-channel exchange has $J = 0$. (On the contrary, a charged $J = 2$ particle would have $\sigma \gg \sigma(WW)$.)

Exclusive QCD dijet production, $X = JJ$, can be selected under a large background with timing $(z_{pp} = z_X)$, longitudinal momentum balance $(p_{zJ1} + p_{zJ2}) = -(p_{zp1} + p_{zp2})$, $\sum_{i=1,2} E_{T,i} = -\sum_{i=1,2} p_{Ti}(p) \sim 0$, with the jets opposite in azimuth ϕ. One can include three jets, and can clean the sample by requiring *track isolation*, i.e. find all the tracks on the jets' common vertex and calculate their transverse momenta k_T with respect to the jet axes. Then select events having no tracks with $k_T \gtrsim 1$ GeV/c. The $M(JJ)$ spectrum itself is a good test of the theory of hard pomeron interactions, which also predicts that $> 99\%$ of these dijets are gluon jets, and the rest are nearly all $b\bar{b}$ jets. This tests the $J_z = 0$ rule [4] which forbids light quark dijets when the protons have $t \sim t_{min}$. So it is important to have very efficient $b-$tagging with few fakes, and both protons measured. The exclusive $b\bar{b}$ dijet spectrum should be measured as well as possible, to test QCD and to estimate the background for $H \to b\bar{b}$.

When only one proton is detected one does not have constraints on the vertex z from timing, or on $M(X)$ from the missing mass to the protons. This will make physics under normal high pile-up conditions very difficult or impossible, except for some particularly clean final states such as exclusive $\tau^+\tau^-, W^+W^-$ or Z with leptonic decays. Single diffractive dijet candidates, with p and JJ, are likely to be from different events. With the HPS operational we can hope for at least some days of special running with average pile-up $\mu \sim 1$. In 120 hours with 2800 bunches and μ = 1 we would have 180 pb^{-1} delivered, and 66 pb^{-1} for single no-pile-up collisions. (Without seeing the protons, about 100 exclusive $\gamma\gamma$ events with $M(\gamma\gamma) > 10$ GeV could be measured, another test of the exclusive Higgs mechanism.) The single diffractive Z and W cross sections are ~ 10 - 100 pb. High mass single diffraction, $p+W,Z,JJ,Q\bar{Q}$ would be extremely valuable to enhance our understanding of QCD in the diffraction sector.

Consider exclusive τ-pair production: $X = \tau^+\tau^-$; the τ's decay to 1-track (85%) or 3 collimated tracks with low mass (15%); 40% of the pairs have an e or μ for a trigger. The τ's will have $\Delta\phi \sim \pi$ and that, together with no other tracks on the τ-pair vertex ($n_{ass.} = 0$), will reject almost all the Drell-Yan background. Three mechanisms can produce this final state: $\gamma+\gamma$, $\gamma+\mathrm{I\!P} \rightarrow Z$, and $\mathrm{I\!P}+\mathrm{I\!P} \rightarrow H$. The first two produce e^+e^- and $\mu^+\mu^-$ with identical spectra., which can be measured as a control. For $|\eta_\tau| < 2.0$ the QED process has $\sigma \sim 100$ fb for $M(\tau^+\tau^-) > 60$ GeV, 22 fb in the Z-region 90$\pm$10 GeV and 5 fb in the H region 125$\pm$5 GeV. $\sigma(Z)$ is predicted to be 6-10 fb [9, 10] in $|\eta| < 2$, but the branching fraction $Z \rightarrow \tau^+\tau^-$ is only 3.4%. The exclusive H(125) cross section is expected to be within a factor ~ 3 of 10 fb, and the branching fraction to $\tau\tau$ to be 6% (so, $18^{\times 3}_{\div 3}$ events in 100 fb^{-1}). Cuts on t_1, t_2 can enhance the signal:background, but although single arm $p + [H(125) \rightarrow \tau^+\tau^-]$ is in the Stage 1 acceptance, and the background may be very small (with $n_{ass.} = 0$ and kinematic contraints), the $H(125)$ signal will be small too. We have acceptance for exclusive Z-photoproduction with one p and $Z \rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-$ (10.4%). Is it interesting? With $\gamma+\mathrm{I\!P} \rightarrow Z$ through quark loops, we do not expect a *surprise*, but it does test some hard pomeron issues, as do photoproduction of J/ψ and Υ, but at higher Q^2.

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